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DUST IN REGIONS OF MASSIVE STAR FORMATION

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Obsevational evidence suggests that stars greater than 100 $M_\odot$ exist in the Galaxy and LMC (Humphreys and Mc Elroy 1984), however classical star formation theory (Larson and Starrfield 1971, Kahn 1974) predict stellar mass limits of only ≈ 60 $M_\odot$. A protostar increases mass by accreting the surrounding gas and dust. Grains are destroyed as they near the central protostar creating a dust shell or cocoon. Radiation pressure acting on the grains can halt the inflow of material thereby limiting the amount of mass accumulated by the protostar. We first consider rather general constraints on the initial dust-to-gas ratio and mass accretion rates that permit inflow. We further constrain these results by constructing a numerical model, including radiative deceleration on grains and grain destruction processes.

At the outer boundary of the flow, grains see the infrared field emitted by warmer grains in the shell's interior . The outward radiative acceleration must be less than the inward gravitational acceleration

$$\Gamma = \left|\frac{\text{radiation}}{\text{gravity}}\right| = \frac{k_F L/4\pi r^2 c}{GM/r^2} < 1 , \tag{1}$$

where k_F is the flux mean of the dust opacity. We approximate k_F by $k_B(T_{\rm rad})$ the Planck mean of the radiation pressure coefficient, where $T_{\rm rad}$ is some characteristic temperature of the radiation field. The maximum of $T_{\rm rad}$ has been chosen to be 2000 K since grains at the cocoon's inner edge will be destroyed before they can be heated to such a temperature. The opacity is calculated using an assumed grain model. As a standard we use the Mathis, Rumpl, and Nordsieck (1977) (MRN) grain model consisiting of graphite and silicate grains ranging in radius between $a_- = 0.005\mu$m and $a_+ = 0.25\mu$m, and distributed in radius as $a^{-3.5}$. Adopting the optical constants of Draine and Lee (1984), we find the outward radiative acceleration exceeds the inward pull of gravity for core masses as low as ~ 10 $M_\odot$. Furthermore, infall onto a 100 $M_\odot$ core is allowed, for a wide range in $T_{\rm rad}$, only if the total grain number abundance is reduced by a factor of 4 relative to the standard MRN grain model and graphite grains larger than 0.2 times the MRN maximum size are depleted.

At the shell's inner edge, the outward radiation pressure must be less than the dynamic pressure of infalling material. If all of the stellar radiation field is absorbed in a thin region at the inner edge of the dust shell, r_1, then it is necessary that

$$\left|\frac{\text{radiation} \quad \text{pressure}}{\text{dynamic} \quad \text{pressure}}\right| = \frac{L/c}{\dot{M} v_{ff}(r_1)} < 1 \tag{2}$$

where $\dot{M}$ is the mass accretion rate and $v_{ff}(r_1)$ is the free-fall velocity at the dust destruction radius, r_1. We estimate the dust destruction radius by equating radiative heating by the central star to radiative cooling at the grain sublimation temperature. Since the free-fall speed is the largest possible inflow speed, we get an estimate of the minimum rate of mass inflow necessary for accretion to continue. Using the largest graphite grain size that satisfies the outer boundary condition, $a_+ = 0.05\mu$m, and assuming here $T_{\rm sub} = 1800$ K, we find that inflow into a 100 $M_\odot$ core requires a mass accretion rate of $> 10^{-3}$ $M_\odot$ yr^{-1}.

Proper estimates of the limits on $\dot{M}$ and the intial grain conditions require us to account for the deceleration of the flow between shell boundaries due to radiation pressure and to calculate grain destruction processes acting in the inflow. Processes of sublimation and vaporization by grain-grain collisions are considered for both graphite and silicates, plus surface reactions for graphites. We use the radiation transfer program of Wolfire and Cassinelli (1986) to calculate the grain temperatures and radiation field throughout the accrection flow. The rate of grain destruction depends mainly on the grain temperature, therefore grains of different sizes and compositions are destroyed at different radial distances.

Accretion onto a 100 $M_\odot$ core was maintained for $\dot{M} = 5 \times 10^{-3}$ $M_\odot$ yr^{-1} and a dust-to-gas ratio of 1/8 times the standard Galactic value. This is a higher mass inflow and lower grain abundance than that estimated by the simple boundary conditions which neglected the deceleration of the flow by infrared radiation.

In conclusion, we have investigated the constraints on dust properties which allows the formation of massive stars. We find the dust-to-gas ratio of the MRN standard model must be reduced by a factor of 4, and graphite grains larger than $\approx 0.05\mu$m in radius must be depleted. Furthermore, the accretion rate onto massive protostars (> 60 $M_\odot$) must be maintained at a fairly large value ($> 10^{-3}$ $M_\odot$ yr^{-1}) during the formation process. These findings seem to suggest that massive star formation requires rather extreme preconditioning of the grain and gas environment.

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